Congressional Research Service
Informing the legislative debate since 1914

Carbon Capture Technology Assessment: In Brief

Updated November 5, 2013

Congressional Research Service
https://crsreports.congress.gov
R43300

CRS REPORT
Prepared for Members and
Committees of Congress

Summary

Carbon capture and sequestration (CCS) is widely seen as a critical strategy for limiting atmospheric emissions of carbon dioxide (CO_2)—the principal "greenhouse gas" linked to global climate change—from power plants and other large industrial sources. This report focuses on the first component of a CCS system, the CO_2 capture process. Unlike the other two components of CCS, transportation and geologic storage, the CO_2 capture component of CCS is heavily technology-dependent. For CCS to succeed at reducing CO_2 emissions from a significant fraction of large sources in the United States, CO_2 capture technologies would need to be deployed widely. Widespread commercial deployment would likely depend, in part, on the cost of the technology deployed to capture CO_2. This report summarizes prospects for improved, lower-cost technologies for each of the three current approaches to CO_2 capture: post-combustion capture; pre-combustion capture; and oxy-combustion capture. CRS Report R41325, *Carbon Capture: A Technology Assessment*, provides a more detailed analysis of these technologies.

While all three approaches are capable of high capture efficiencies (typically about 90%), the major drawbacks of current processes are their high cost and the large energy requirements for operation. Another drawback is that at present there are still no full-scale applications of CO_2 capture on a coal-fired or gas-fired power plant; these plants produce over a third of total U.S. CO_2 emissions from fossil fuel combustion. However, a number of large-scale demonstration projects at both coal combustion and gasification-based power plants are planned or underway in the United States and elsewhere. Substantial research and development (R&D) activities are also underway in the United States and elsewhere to develop and commercialize lower-cost capture systems with smaller energy penalties. Current R&D activities include development and testing of new or improved solvents that can lower the cost of current post-combustion and pre-combustion capture, as well as research on a variety of potential "breakthrough technologies" such as novel solvents, sorbents, membranes, and oxyfuel systems that hold promise for even lower-cost capture systems.

The future use of coal in the United States will likely depend on whether and how CCS is deployed if legislative or regulatory actions curtail future CO_2 emissions. Congressional interest in CCS was renewed when the U.S. Environmental Protection Agency (EPA) re-proposed standards for carbon dioxide (CO_2) emissions from new fossil-fueled power plants on September 20, 2013. These re-proposed standards would not apply to existing power plants. As re-proposed, the standards would limit emissions of CO_2 to no more than 1,100 pounds per megawatt-hour of production from new coal-fired power plants and between 1,000 and 1,100 for new natural gas-fired plants. According to EPA, new natural gas-fired stationary power plants should be able to meet the proposed standards. However, new coal-fired plants only would be able to meet the standards by installing CCS technology, which could add significant capital costs.

In general, the focus of most current R&D activities is on cost reduction rather than additional gains in CO_2 capture efficiency. Key questions include: when would advanced CO_2 capture systems be available for commercial rollout; and how much cheaper they would be compared to current technology. "Technology roadmaps" developed by governmental and private-sector organizations anticipate that CO_2 capture may be available for commercial deployment at power plants by 2020. Some roadmaps also project that some novel, lower-cost technologies may be commercial by 2020. Such projections acknowledge, however, that this will require aggressive efforts to advance promising concepts to commercial viability.

Achieving significant cost reductions would likely require a vigorous and sustained level of R&D and also a significant market for CO_2 capture. At present such a market does not exist. While various types of incentive programs can accelerate the development and deployment of CO_2

capture technology, actions that significantly limit emissions of CO_2 to the atmosphere ultimately would be needed to realize substantial and sustained reductions in the future cost of CO_2 capture.

Contents

Figures

Tables

Contacts

Introduction

Congressional interest in carbon capture and sequestration (or carbon capture and storage, CCS) has been renewed since the U.S. Environmental Protection Agency (EPA) re-proposed standards for carbon dioxide (CO_2) from new fossil-fueled power plants on September 20, 2013. As re-proposed, the standards would limit emissions of CO_2 to no more than 1,100 pounds per megawatt-hour of production from new coal-fired power plants and between 1,000 and 1,100 (depending on size of the plant) for new natural gas-fired plants. The standards would not apply to existing facilities. EPA proposed the standard under Section 111 of the Clean Air Act.[1] According to EPA, new natural gas-fired stationary power plants should be able to meet the proposed standards without additional cost or the need for add-on control technology. However, new coal-fired plants only would be able to meet the standards by installing carbon capture and sequestration (CCS) technology. The proposed standard would allow an option of up to seven years for a new coal-fired plant to comply. But that option would require a more stringent standard for those plants and limit CO_2 emissions to an average of 1,000-1,050 pounds per megawatt-hour over the seven-year period.

The promise of CCS lies in the potential for technology to capture CO_2 emitted from large, industrial sources, thus significantly decreasing CO_2 emissions without drastically changing U.S. dependence on fossil fuels, particularly coal, for electricity generation. The future use of coal—a significant component of the U.S. energy portfolio—in the United States will likely depend on whether and how CCS is deployed if legislative or regulatory actions curtail future CO_2 emissions. The September 20, 2013, proposed rule for limiting CO_2 emissions from new fossil-fueled power plants is one such action. In addition, Section 111 of the Clean Air Act requires that EPA develop guidelines for pollutants—which has been interpreted to include greenhouse gas emissions—for existing plants whenever it promulgates standards for new power plants. In a June 25, 2013, memorandum, President Obama directed the EPA to issue proposed guidelines for existing plants by June 1, 2014, and to issue final guidelines a year later.[2] These proposed actions will likely draw additional congressional scrutiny of the viability of large-scale CCS as the primary technology for mitigating CO_2 emissions from coal-fired power plants.

Unlike the other two components of CCS, transportation and geologic storage, the first component of CCS—CO_2 capture—is almost entirely technology-dependent. For CCS to succeed at reducing CO_2 emissions from a significant fraction of large sources in the United States, CO_2 capture technology would need to be deployed widely. Widespread commercial deployment would likely depend on the cost of capturing CO_2, although other factors, such as incentives for reducing greenhouse gas emissions, would also influence deployment.

The transportation and storage components of CCS are not nearly as technology-dependent as the capture component. Nonetheless, transportation and sequestration costs, while generally much smaller than capture costs, could be very high in some cases. They would depend, in part, on how long it would take to reach an agreement on a regulatory framework to guide long-term CO_2

---

[1] Since 2009, EPA has begun to address emissions of greenhouse gases from both mobile and stationary sources, using broad regulatory authority provided by Congress decades ago in the Clean Air Act. Although Congress has never specifically directed EPA to regulate emissions of greenhouse gases, the Clean Air Act as enacted in 1970 and as amended in 1977 and 1990 gave the agency authority to identify air pollutants and promulgate regulations to limit their emission. For more information see CRS Report R43127*, EPA Standards for Greenhouse Gas Emissions from Power Plants: Many Questions, Some Answers*, by James E. McCarthy.

[2] Office of the Press Secretary, The White House, "Power Sector Carbon Pollution Standards," Memorandum for the Administrator of the Environmental Protection Agency, June 25, 2013, http://www.whitehouse.gov/the-press-office/2013/06/25/presidential-memorandum-power-sector-carbon-pollution-standards.

injection and storage, and on what those regulations would require. CCS deployment would also depend on the degree of public acceptance of a large-scale CCS enterprise. Several CRS reports (see below) address these policy issues of CO_2 transportation and storage.

Structure of this Report

This report is a brief summary of a longer study—CRS Report R41325, *Carbon Capture: A Technology Assessment*—that provides a "snapshot" of technological development current through mid-2010. The technology assessment is both prospective and retrospective in that it examines emerging or advanced technologies that may affect future CCS deployment, and looks at lessons from past experience with large-scale technological development and deployment as guidelines that could be used to shape energy policy. The longer report consists of 10 chapters, together with figures and tables.

This report and the longer CRS report focus on the first component of a CCS system, namely, the CO_2 capture process. The goal of these reports is to provide a realistic assessment of prospects for improved, lower-cost technologies for each of the three current approaches to CO_2 capture.

The technology assessment was undertaken by Carnegie Mellon University, Department of Engineering and Public Policy, under the leadership of Edward S. Rubin, together with Aaron Marks, Hari Mantripragada, Peter Versteeg, and John Kitchin. The work was performed under contract to CRS, and is part of a multiyear CRS project to examine different aspects of U.S. energy policy. Peter Folger, CRS Specialist in Energy and Natural Resources Policy, served as the CRS project coordinator.

CRS Report R41325, *Carbon Capture: A Technology Assessment*, was funded, in part, by a grant from the Joyce Foundation.

Other CRS Reports on CCS

CRS has written a suite of products on different aspects of CCS that complement this assessment of carbon capture technologies. These include:

- CRS Report R42532, *Carbon Capture and Sequestration (CCS): A Primer*, by Peter Folger.
- CRS Report R42496, *Carbon Capture and Sequestration: Research, Development, and Demonstration at the U.S. Department of Energy*, by Peter Folger.
- CRS Report R43028, *FutureGen: A Brief History and Issues for Congress*, by Peter Folger.
- CRS Report R42950, *Prospects for Coal in Electric Power and Industry*, by Richard J. Campbell, Peter Folger, and Phillip Brown.
- CRS Report RL33971, *Carbon Dioxide (CO2) Pipelines for Carbon Sequestration: Emerging Policy Issues*, by Paul W. Parfomak, Peter Folger, and Adam Vann.
- CRS Report R40103, *Carbon Control in the U.S. Electricity Sector: Key Implementation Uncertainties*, by Paul W. Parfomak.
- CRS Report RL34316, *Pipelines for Carbon Dioxide (CO2) Control: Network Needs and Cost Uncertainties*, by Paul W. Parfomak and Peter Folger.

- CRS Report RL34307, *Legal Issues Associated with the Development of Carbon Dioxide Sequestration Technology*, by Adam Vann and Paul W. Parfomak.
- CRS Report RL34601, *Community Acceptance of Carbon Capture and Sequestration Infrastructure: Siting Challenges*, by Paul W. Parfomak.
- CRS Report R43127, *EPA Standards for Greenhouse Gas Emissions from Power Plants: Many Questions, Some Answers*, by James E. McCarthy.

Background

Global climate change is an issue of major international concern and the focus of proposed mitigation policy measures in the United States and elsewhere. In this context, CCS technology has received increasing attention over the past decade as a potential method of limiting atmospheric emissions of CO_2—the principal "greenhouse gas" linked to climate change.

Worldwide interest in CCS stems principally from three factors. First is a growing consensus that large reductions in global CO_2 emissions are needed to avoid serious climate change impacts.[3] Because electric power plants are a major source of CO_2, curtailing their emissions has become a focus.

Second is the growing realization that large emission reductions cannot be achieved easily or quickly simply by using less energy or by replacing fossil fuels with alternative energy sources that emit little or no CO_2. The reality is that the world (and the United States itself) today relies on fossil fuels for over 85% of its energy use (including fuel for transportation, not just electricity generation). Changing that picture dramatically would take time. CCS thus offers a way to get large CO_2 reductions from power plants and other industrial sources until cleaner, sustainable energy technologies can be widely deployed.

Finally, energy-economic models show that adding CCS to the suite of other GHG reduction measures significantly lowers the cost of mitigating climate change. Studies also have affirmed that by 2030 and beyond, CCS is a major component of a cost-effective portfolio of emission reduction strategies.[4]

Figure 1 depicts the overall CCS process applied to a power plant or other industrial process. The CO_2 produced from carbon in the fossil fuels or biomass feedstock is first captured, then compressed to a dense liquid to facilitate its transport and storage. The main storage option is underground injection into a suitable geological formation.

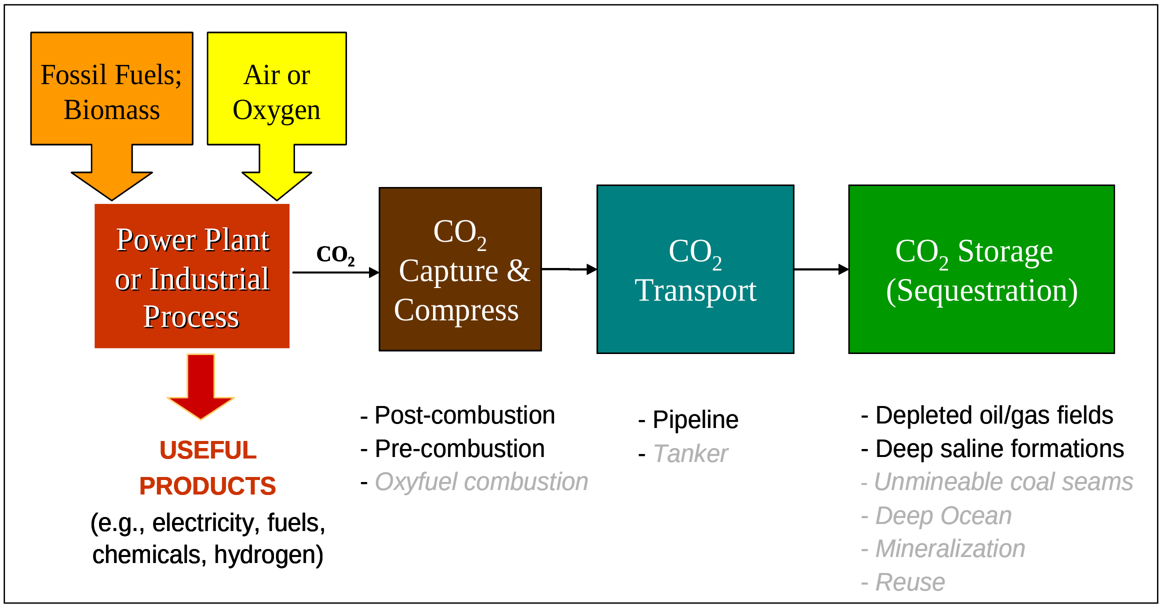
At the present time, CCS is not commercially proven in the primary large-scale application for which it is envisioned—electric power plants fueled by coal or natural gas. Furthermore, the cost of CCS today is relatively high, due mainly to the high cost of CO_2 capture (which includes the cost of CO_2 compression needed for transport and storage). This has prompted a variety of government and private-sector research programs in the United States and elsewhere to develop more cost-effective methods of CO_2 capture.

---

[3] National Research Council, *America's Climate Choices: Limiting the Magnitude of Future Climate Change*, The National Academies Press, Washington, DC, May 2010; S. Solomon et al., eds., *Climate Change 2007: The Physical Science Basis*, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, 2007.

[4] J. Edmonds, "The Potential Role of CCS in Climate Stabilization," Proc. *9th International Conference on Greenhouse Gas Control Technologies, 2008*, Washington, DC; B. Metz, et al., eds., *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Figure 1. Schematic of a CCS System, Consisting of CO2 Capture, Transport, and Storage



Source: E. S. Rubin, "Will Carbon Capture and Storage be Available in Time?," American Association for the Advancement of Science, Annual Meeting, San Diego, CA, February 18-22, 2010.

Notes: Carbon inputs may include fossil fuels and biomass. Technical options are listed below each stage. Those in italics are not available or implemented at a commercial scale.

Overview

The following is an assessment of prospects for CCS capture technologies; namely, post-combustion capture from power plant flue gases using amine-based solvents such as monoethanolamine (MEA) and ammonia; pre-combustion capture (also via chemical solvents) from the synthesis gas produced in an integrated coal gasification combined cycle (IGCC) power plant; and oxy-combustion capture, in which high-purity oxygen rather than air is used for combustion in a pulverized coal (PC) power plant to produce a flue gas with a high concentration of CO_2 amenable to capture without a post-combustion chemical process.

Currently, post-combustion and pre-combustion capture technologies are commercial and widely used for gas stream purification in a variety of industrial processes. Several small-scale installations also capture CO_2 from power plant flue gases to produce CO_2 for sale as an industrial commodity. Oxy-combustion capture, however, is still under development and is not currently commercial.

The advantages and limitations of each of these three methods are discussed in CRS Report R41325, *Carbon Capture: A Technology Assessment*, along with plans for their continued development. While all three approaches are capable of high CO_2 capture efficiencies (typically about 90%), the major drawbacks of current processes are their high cost and the large energy requirement for operation (which significantly reduces the net plant capacity and contributes to the high cost of capture). Another drawback in terms of their availability for greenhouse gas mitigation is that at present, there are still no applications of CO_2 capture on a coal-fired or gas-fired power plant at full scale (i.e., a scale of several hundred megawatts of plant capacity).

Current Research and Development (R&D) Activities

To address the current lack of demonstrated capabilities for full-scale CO_2 capture at power plants, a number of large-scale demonstration projects at both coal combustion and gasification-based power plants are planned or underway in the United States and elsewhere. These projects and the technologies they plan to employ are summarized in CRS Report R41325, *Carbon Capture: A Technology Assessment*. Many of these demonstrations are expected to begin operation in 2014 or 2015. Planned projects for other types of industrial facilities also are discussed.

Also elaborated in the longer report are the substantial R&D activities underway in the United States and elsewhere to develop and commercialize lower-cost capture systems with smaller energy penalties. To characterize the status of capture technologies and the prospects for their commercial availability, five stages of development are defined: conceptual designs; laboratory or bench scale; pilot plant scale; full-scale demonstration plants; and commercial processes. The CRS report reviews current activities at each of these stages for each of the three major capture routes.

Current R&D activities include development and testing of new or improved solvents that can lower the cost of current post-combustion and pre-combustion capture, as well as research on a variety of potential "breakthrough technologies" such as novel solvents, sorbents, membranes, and oxyfuel systems that hold promise for even lower-cost capture systems. Most of the latter processes, however, are still in the early stages of research and development (i.e., conceptual designs and laboratory- or bench-scale processes), so that credible estimates of their performance and (especially) cost are lacking at this time. **Table 1** lists the major approaches being pursued for post-combustion capture, although many of these approaches apply to pre-combustion and oxy-combustion capture as well.

Table 1. Post-Combustion Capture Approaches Being Developed at Laboratory or Bench Scale

Liquid Solvents	Solid Adsorbents	Membranes
Advanced amines	Supported amines	Polymeric
Potassium carbonate	Carbon-based	Amine-doped
Advanced mixtures	Sodium carbonate	Integrated with absorption
Ionic liquids	Crystalline materials	Biomimetic-based

Source: Edward S. Rubin, Aaron Marks, Hari Mantripragada, Peter Versteeg, and John Kitchin, Carnegie Mellon University, Department of Engineering and Public Policy.

Processes under development at the more advanced pilot plant scale are, for the most part, new or improved solvent formulations (such as ammonia and advanced amines) that are undergoing testing and evaluation. These advanced solvents could be available for commercial use within several years if subsequent full-scale testing confirms their overall benefit. Pilot-scale oxy-combustion processes also are currently being tested and evaluated for planned scale-up, while two IGCC power plants in Europe are installing pilot plants to evaluate pre-combustion capture options.

In general, the focus of most current R&D activities is on cost reduction rather than additional gains in the efficiency of CO_2 capture (which can result in cost increases rather than decreases). A number of R&D programs emphasize the need for lower-cost retrofit technologies suitable for existing power plants. As a practical matter, however, most technologies being pursued to reduce capture costs for new plants also apply to existing plants. As the fleet of existing coal-fired power plants continues to age, the size of the potential U.S. retrofit market for CO_2 capture will continue to shrink, as older plants may not be economic to retrofit (although the situation in other countries, especially China, may be quite different).

Future Outlook

Whether for new power plants or existing ones, the key questions are the same: When would advanced CO_2 capture systems be available for commercial rollout, and how much cheaper would they be compared to current technology?

To address the first question, CRS Report R41325, *Carbon Capture: A Technology Assessment*, reviews a variety of "technology roadmaps" developed by governmental and private-sector organizations in the United States and elsewhere. All of these roadmaps anticipate that CO_2 capture will be available for commercial deployment at power plants by 2020. Current commercial technologies like post-combustion amine systems could be available sooner. A number of roadmaps also project that novel, lower-cost technologies like solid sorbent systems for post-combustion capture will be commercial in the 2020 time frame. Such projections acknowledge, however, that this will require aggressive and sustained efforts to advance promising concepts to commercial reality.

That caveat is strongly supported by a review of experience from other recent R&D programs to develop lower-cost technologies for post-combustion SO_2 and NO_x capture at coal-fired power plants. Those efforts typically took two decades or more to bring new concepts (like combined SO_2 and NO_x capture processes) to commercial availability. By then, however, the cost advantages initially foreseen for these novel systems had largely evaporated in most cases: the advanced technologies tended to get more expensive as their development progressed (consistent with "textbook" descriptions of the innovation process), while the cost of formerly "high-cost" commercial technologies gradually declined over time. The absence of a significant market for the novel technologies put them at a further disadvantage. This may be similar to the situation for CO_2 capture systems today. Thus, the development of advanced CO_2 capture technologies is not without financial risks.

With regard to future cost reductions, based on past experience, the costs of environmental technologies that succeed in the marketplace tend to fall over time. For example, after an initial rise during the early commercialization period, the cost of post-combustion SO_2 and NO_x capture systems declined by 50% or more after about two decades of deployment at coal-fired power plants. This trend is consistent with the "learning curve" behavior seen for many other classes of technology. It thus appears reasonable to expect a similar trend for future CO_2 capture costs once these technologies become widely deployed. Note, too, that the cost of CO_2 capture also depends on other aspects of power plant design, financing, and operation—not solely on the cost of the CO_2 capture unit. Future improvements in net power plant efficiency, for example, would tend to lower the unit cost of CO_2 capture.

Other cost estimates for advanced CO_2 capture systems are based on engineering-economic analysis of proposed system designs. For example, recent studies by the U.S. Department of Energy (DOE) foresee the cost of advanced PC and IGCC power plants with CO_2 capture falling by 27% and 31%, respectively, relative to current costs as a result of successful R&D programs. No estimates are provided, however, as to when the various improvements described are expected to be commercially available. In general, the farther away a technology is from commercial reality, the lower its estimated cost tends to be. Thus, there is considerable uncertainty in cost estimates for technologies that are not yet commercial, especially those that exist only as conceptual designs.

More reliable estimates of future technology costs typically are linked to projections of their expected level of commercial deployment in a given time frame (i.e., a measure of their market size). For power plant technologies like CO_2 capture systems, this is commonly expressed as total installed capacity. However, as with other technologies whose sole purpose is to reduce environmental emissions, there is no significant market for power plant CO_2 capture systems absent government actions or policies that effectively create such markets—either through regulations that limit CO_2 emissions, or through voluntary incentives such as tax credits or direct financial subsidies. The technical literature and historical evidence examined in CRS Report R41325, *Carbon Capture: A Technology Assessment*, strongly link future cost reductions for CO_2 capture systems to their level of commercial deployment. In widely used models based on empirical "experience curves," the latter measure serves as a surrogate for the many factors that influence future technology costs, including the level of R&D expenditures and the new knowledge gained through learning-by-doing (related to manufacturing) and learning-by-using (related to technology use).

Based on such models, published estimates project the future cost of electricity from power plants with CO_2 capture to fall by as much as 30% below current values after roughly 100,000 megawatts (MW) of capture plant capacity is installed and operated worldwide. That estimate is in line with the DOE projects noted above. If achieved, it would represent a significant decrease from current costs—one that would bring the cost and efficiency of future power plants with CO_2 capture close to that of current plants without capture. For reference, it took approximately 20 years following passage of the 1970 Clean Air Act Amendments to achieve a comparable level of technology deployment for SO_2 capture systems at coal-fired power plants.

Uncertainty estimates for these projections, however, indicate that future cost reductions for CO_2 capture also could be much smaller than indicated above. Thus, whether future cost reductions would meet, exceed, or fall short of current estimates will only be known with hindsight.

In the context of this report and CRS Report R41325, *Carbon Capture: A Technology Assessment*, the key insight governing prospects for improved carbon capture technology is that achieving significant cost reductions would require not only a vigorous and sustained level of R&D, but also a substantial level of commercial deployment. That would necessitate a significant market for CO_2 capture technologies. At present such a market does not exist. While various types of incentive programs can accelerate the development and deployment of CO_2 capture technology, actions that significantly limit emissions of CO_2 to the atmosphere ultimately would be needed to realize substantial and sustained reductions in the future cost of CO_2 capture.

Author Information

Peter Folger
Specialist in Energy and Natural Resources Policy

Disclaimer